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STUDY OF THE INTER-RELATIONSHIP
THERBLIG TIMES.

A STUDY OF THE INTER-RELATIONSHIP

OF THERBLIG TIMES

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ABSTRACT

The purpose of the experiment was to test the hypothesis that time values for certain therbligs cannot be given as universal values since they are influenced by other therbligs in the sequence.

The equipment for the experiment was designed so that time values for the individual therbligs of a given sequence could be obtained. The experiment was divided into three parts which were called setups. Setups B and C differed from Setup A in that the therblig sequences were changed. The change in therblig sequence was accomplished by requiring a more difficult position and assemble at one station.

The therblig sequence was made up of transport empty (T_1) from station 1 to station 2, grasp a two inch hollow metal cube at station 2, transport loaded (T_2) from station 2 to station 3, position and assemble of the cube at station 3, release load at station 3, transport empty (T_3) from station 3 to station 1, contact grasp at station 1, transport empty (T_4) from station 1 to station 3, grasp and disassemble the cube at station 3, transport loaded (T_5) from station 3 to station 2, position and release load cube at station 2, and transport empty (T_6) to station 1. In Setup A, only a rough position and assemble were required at station 3 since the cube was placed in a four

inch circular container. In Setup B, a more difficult position and assemble were required as the container was changed to a square box 2-1/4 inches on the inside edge. In Setup C, the square box was replaced by a plate with two 1/2 inch dowels attached. The cube had two 5/8 inch holes in the bottom and had to be placed on the dowels. By changing the device at station 3 as outlined above, the six transports, T_1 through T_6, remained the same.

Twelve operators performed ten cycles of each setup. The setups were presented to the operators in a planned sequence to allow for any learning during the experiment. Each operator was given approximately twenty minutes training before starting the experiment, and the chair was adjusted so that elbow height was standardized.

A kymograph was used to record the elapsed time for the therbligs. Signals were transmitted to the kymograph by the interruption or completion of various electrical circuits. Two photoelectric cells were used to obtain the terminal points of the two transports which were followed by a position therblig.

The kymograph tape was measured in fiftieths of an inch, and the data was tabulated for each operator and setup.

Analysis of variance was employed to determine if the time values for the six transports under the three experimental setups were significantly different. It was found

that the time values for the transports T_2, T_3, T_5, and T_6 under the three setups were significantly different at the one percent level. The transports T_1 and T_4 were not apparently affected by the change in therblig sequence.

The components of variation were computed and it was found that the change in setups contributed a smaller percentage of the total variation than the operators, interaction of operators versus setups, or the error. The important fact was, of course, that the change in setups did contribute to the significant difference.

For the operators who participated in the experiment and under the conditions which prevailed, the following conclusions can be stated:

1. The evidence obtained as the result of this experiment supports the hypothesis that time values for certain therbligs (transport empty and transport loaded) cannot be given as universal values since they are affected by other therbligs in the motion sequence.
2. Several causative factors were suggested, but more evidence is needed to assign a reason for the observed variation.

A STUDY OF THE INTER-RELATIONSHIP OF THERBLIG TIMES

INTRODUCTION

The term "therblig" was coined by Frank B. and Lillian M. Gilbreth about thirty years ago to identify elementary subdivisions of human activity. With only slight modification the original classification of hand and body motions has stood the test of time and is widely used by conventional motion and time study practitioners. For an excellent discussion of therbligs, see the motion and time study textbook by Barnes[1] or Mundel[2].

One of the drawbacks of stop-watch time studies is the fact that the time studies cannot be performed until the job or task is in operation. It would obviously be advantageous to be able to set accurate time standards for jobs before the jobs were actually commenced. In this way the relative merit of several variations of any job could easily be evaluated before any costly setups were undertaken.

The advent of the predetermined motion-time systems supposedly eliminated another disadvantage of the

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[1]Barnes, R. M., Motion and Time Study; New York, John Wiley and Sons, 1949, chapter 9.

[2]Mundel, M. E., Motion and Time Study Principles and Practice; New York, Prentice-Hall, 1950, chapter 12.

conventional approach. The authors of Methods-Time Measurement[3] claim, among other things, that their system eliminates the subjective judgment required of the observer when the performance of the operator is rated. On the other hand they admit that a certain degree of judgment is still required to determine what motions are necessary to perform a particular operation.

Most of the time values for the predetermined motion-time systems have been obtained through the analysis of motion pictures. The nature of the basic motions and the conditions under which they are performed have been carefully defined. Thus, through a knowledge of the basic motions which make up a particular job, the basic time values may be applied to obtain the standard time for the job. The question whether the time values assigned to the basic motions by the predetermined motion-time systems can be considered to be universal is the chief concern of this research. A very thorough discussion of some previous research conducted at Purdue University and Washington University has been presented by Nadler.[4] This presentation set forth some interesting results which clearly reflect

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[3]Maynard, H. B., Stegermerten, G. J., and Schwab, J. L. Methods-Time Measurement; New York, McGraw-Hill Book Company Inc., 1948.

[4]Nadler, G., "Critical Analysis of Motion Time Systems," Sixteenth Annual National Time and Motion Study and Management Clinic Proceedings, Industrial Management Society, Chicago, 1952.

that therbligs, or basic motions, should be considered qualitatively instead of quantitatively.

The conclusions of some research performed by Barnes and Mundel state, in part as follows: "Hence, it is suggested that the standard times for certain therbligs cannot be given as independent values since they may be influenced by other therbligs in the cycle."[5]

As the result of an investigation concerning elemental and therblig times at various levels of activity, Schwab concludes:

"1. The rating of one therblig or a group of therbligs does not give a valid rating for the whole cycle.

"2. Elemental and therblig times are not proportional from one level of activity to another, i.e., the times to perform most therbligs does increase as the rate of activity decreases, but in no set pattern.

"3. The use of therblig time values to obtain rates of activity and the extension of these rates to cover the whole cycle does not yield a true rate for the overall job.

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[5]Barnes, R. M., and Mundel, M. E., "A Study of Hand Motions Using the Photoelectric Cell and the Kymograph," University of Iowa Studies in Engineering, Bulletin 12, March 1938, p. 30.

"4. The use of elemental time values to obtain rates of activity and the extension of the rates to cover the overall cycle does not yield a true rate for the whole job."[6]

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[6] Schwab, P. W., Jr., An Investigation to Determine the Proportionality of Elemental and Therblig Times at Typical Levels of Factory Activity, Unpublished Master Thesis, Purdue University, 1948.

PURPOSE

The purpose of this investigation was to test the hypothesis that time values for certain therbligs cannot be given as universal values since they are influenced by other therbligs in the motion sequence.

In the analysis of some research reported on by Nadler and Wilkes,[7] time values were tabulated for several groups of therbligs. A review of the motion sequence used in their research indicated that more therbligs were included than were actually accounted for in the discussion.

In testing the hypothesis stated above, a secondary objective was to separate the therbligs so that any variation discovered might be attributed to a particular therblig instead of a group of therbligs.

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[7] Nadler, G., and Wilkes, J. W., "Studies in Relationships of Therbligs," Advanced Management, February, 1953.

EQUIPMENT

The experiment was designed to enable time values for individual therbligs to be obtained. Since the gross movement therbligs, transport empty and transport loaded, are a part of almost every job, it was decided to construct a simple task which contained several of these therbligs. In addition to the above requirement, the task as designed had to be constructed so that it would be possible to vary some of the therbligs in the sequence without disturbing others. The experiment was divided into three parts called setups, and each setup involved a sequence of therbligs which was required to traverse a path (see Figure 1) from station 1 to station 1 via stations 2 and 3 and the reverse path back to the starting point.

Setup A (Figure 1) involved a transport empty of eighteen inches from station 1 directly away from the operator to station 2, a grasp of a two inch hollow metal cube at station 2, a transport loaded of twelve inches with the cube from station 2 to station 3 along a path perpendicular to the path traversed between stations 1 and 2, a rough position of the cube in a circular container four inches in diameter located at station 3, a release load of the cube in the circular container, and a transport empty from station 3 to station 1. From station 1 the direction of the path was reversed. For this portion of Setup A the

Fig. 1 View of Setup A

therblig sequence was made up of a transport empty from station 1 to station 3, a grasp of the cube at station 3, a transport loaded with the cube to station 2, a position of the cube at station 2, a release load of the cube, and a transport empty to station 1.

In Setup B (Figure 2) a square container two and one-fourth inches on the inside edge was substituted for the circular container used in Setup A. The therblig sequence involved in Setup B was thus changed to include an assemble at station 3 as well as requiring a finer degree of position at that station. On the reverse path a disassemble was required at station 3 before the transport loaded from station 3 to station 2 could be performed. Except for the above mentioned changes, the therbligs required for Setup B were identical with those required for Setup A.

In Setup C (Figure 3) the change was again made at station 3. A plate with two one-inch lengths of one-half inch hard wood dowel attached was substituted for the square container used in Setup B. The metal cube had two five-eighths inch holes in the bottom and had to be slipped over the dowels. No new therbligs were introduced in Setup C, however, a hidden position had to be completed before the assemble could be accomplished. The reverse path of Setup C required the same therbligs as were used in the reverse path of Setup B.

In order to be able to obtain time values for the

Fig. 2 View of Setup B

Fig. 3 View of Setup C

individual therbligs involved in the three parts of the experiment, a kymograph (Figure 4) was employed.[8] A mesh of fine copper wire was affixed to the thumb of a right hand glove (Figure 5), and the wire mesh was connected to a multi-volt transformer which was used as the power source. The pens on the kymograph were actuated by solenoids which required a 110 volt power source. The use of the six volt position on the multi-volt transformer as the power source for all operator-completed circuits was made possible by the use of relays. The possibility of an operator receiving a shock was thereby eliminated. Station 1 was a small aluminum angle which was connected to the kymograph through a relay. When the thumb was in contact with station 1, a circuit was completed, and a solenoid actuated pen 1 on the kymograph. At station 2 the bottom of the locater for the cube was an aluminum plate which was connected to the kymograph through a relay. When the thumb touched the cube which was resting on the bottom of the locater, a circuit was completed and a solenoid actuated pen 2 on the kymograph. When the cube was removed from the bottom of the locater, the circuit was broken and pen 2 on the kymograph returned to its original position. Also located at station ? was a photoelectric cell which was in a circuit to pen 3

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[8]Barnes and Mundel, loc. cit.

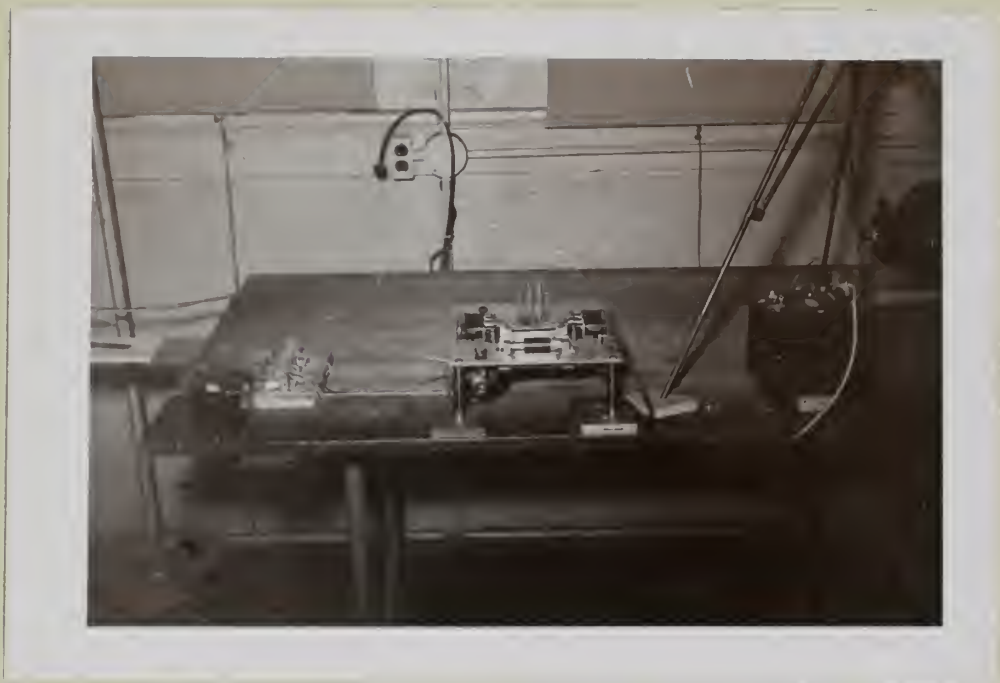

Fig. 4 View of Kymograph

Fig. 5 View of Wire Mesh on Thumb

on the kymograph. To avoid obstructing the work path, the photoelectric cell was mounted beneath the work surface, and the light source, a 75 watt spot, was mounted vertically above station 2. A three-eighths inch hole in the bottom of the locater and the work table permitted the light to fall upon the photoelectric cell when the cube was removed from the locater. This completed a circuit and a solenoid actuated pen 3 on the kymograph.

At station 3 the interchangeable devices mentioned above were all equipped with aluminum bottoms. When the thumb was in contact with the cube, and the cube was placed in the container, a circuit was completed through a relay and a solenoid actuated pen 4 on the kymograph. Removal of the thumb from the cube broke the circuit and pen 4 returned to its original position. A photoelectric cell was mounted at station 3 in the same manner as outlined above for station 2. This photoelectric cell was in a circuit which operated pen 5 on the kymograph.

The kymograph drive was powered by a constant speed motor which drew the paper tape under the solenoid operated pens at an almost constant velocity of 11.1 inches in one-fiftieth of a minute. A test was conducted during which fourteen one-fiftieth of a minute pulses of current were transmitted to the kymograph. The fourteen tapes were measured to the nearest fiftieth of an inch, and the average of 11.1 inches was obtained. The average

variation was less than one-tenth of an inch. This result was thought to be satisfactory for the purpose of this experiment.

Figure 6 shows a reproduction of the record made by the solenoid operated pens on the kymograph tape. A deflection in line 1, 2, or 4 shows that a circuit has been completed or interrupted by the wire mesh on the operator's thumb at station 1, 2, or 3, respectively. A deflection in line 3 or 5 shows that a circuit has been completed or interrupted by action of the photoelectric cell at station 2 or 3, respectively. At the start of the tape it will be noted that lines 1 and 3 were deflected. This means that the operator's thumb was in contact with station 1, and the cube was in position at station 2. Lines 2, 4, and 5 were in their normal position which means that these circuits were open. Transport 1 (T_1) was a transport empty from station 1 to station 2. T_1 on the tape shows that it was measured from the instant contact was broken at station 1 until the instant contact was made at station 2. Transport 2 (T_2) was a transport loaded from station 2 to station 3. T_2 on the tape shows that it was measured from the instant contact was broken at station 2 until the instant that the photoelectric cell was actuated at station 3. Transport 3 (T_3) was a transport empty from station 3 to station 1. T_3 on the tape shows that it was measured from the instant contact was broken at station 2 until the

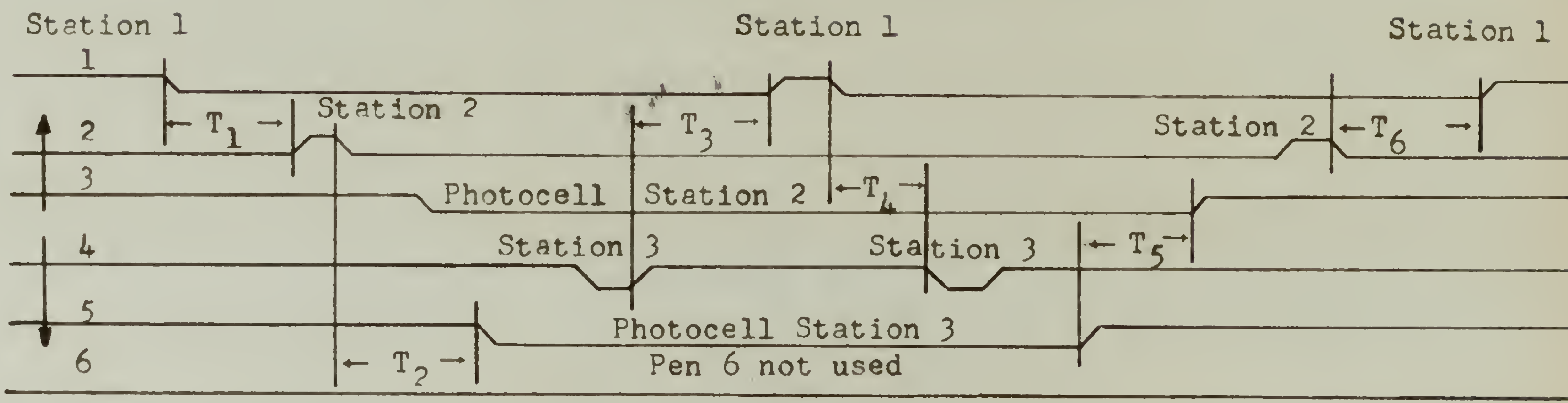

Fig. 6 Reproduction of Record Made by Solenoid Operated Pens on Kymograph Tape

instant contact was made at station 1. Transport 4 (T_4) was a transport empty from station 1 to station 3. T_4 on the tape shows that it was measured from the instant contact was broken at station 1 until the instant contact was made at station 3. Transport 5 (T_5) was a transport loaded from station 3 to station 2. T_5 on the tape shows that it was measured from the instant the photoelectric cell at station 3 was actuated until the instant that the photoelectric cell at station 2 was actuated. Transport 6 (T_6) was a transport empty from station 2 to station 1. T_6 on the tape shows that it was measured from the instant contact was broken at station 2 until the instant contact was made at station 1. As the arrows at the beginning of the tape indicate, kymograph pens 1, 2, and 3 deflect in the opposite direction from pens 4, 5, and 6. Pen 6 was not used during this experiment.

Figure 7 of Appendix A shows the wiring diagram for the experiment.

PROCEDURE

Twelve naval officer students in Industrial Engineering at Purdue University were chosen as operators for the experiment. Each operator viewed the equipment and was given a thorough explanation of the procedure to be used during the administration of the experiment. Figure 8 of Appendix A shows the instructions which were given to each operator before the practice session and again before the recorded runs. Each operator was given approximately twenty minutes of practice to familiarize him with the equipment. Since the two inch metal cube weighed only four ounces and the recorded runs of ten cycles each were extremely short, it was felt that the element of fatigue could be neglected. In order to make final preparations for the recorded runs and to standardize the administration of the experiment as much as possible, each operator was given about five minutes rest before any recorded run was made. Although it was considered that the twenty minute training period given to each operator was sufficient to make any further allowance for learning during the experiment unnecessary, it was felt that an orderly presentation would be desirable. Since there were twelve operators and six permutations of the three experiment setups, a planned presentation was thought to be more in order than any presentation which could be achieved through the

use of a table of random numbers. Figure 9 of Appendix A gives the order of presentation which was used for the administration of the experiment.

Prior to the beginning of the experiment, the elbow height of each operator was measured while he was seated in front of the work table. By the use of plywood blocks of various thicknesses, the chair was adjusted so that the elbow height of all operators was standardized at thirty-five inches above floor level.

The position of the chair was adjusted relative to the work table so that the reach of all operators was the same. The chair was positioned so that each operator, with his arm and fingers comfortably outstretched, could reach a line on the work table. This line was four inches to the rear of and parallel to a line between station 2 and station 3.

When the operator completed the recorded run for a particular setup, the kymograph tape was marked with the operator and setup designator and placed in safekeeping to await analysis.

RESULTS

Tables 1 through 12 contain the data obtained for the six transports, T_1 through T_6, for each operator. The data are recorded in fiftieths of an inch as measured from the kymograph tape (Figure 6).

Table 13 records the mean values for the twelve operators for each of the six transports under the three different setups. These data are also recorded in fiftieths of an inch.

Table 15 of Appendix B shows the results of the analysis of variance.[9] The computational procedures upon which Table 15 was obtained are outlined in Appendix B.

Table 17 of Appendix C gives the results of the computation of the components of variation.[10] Appendix C outlines the procedures followed in computing the components of variation.

Table 19 of Appendix D records the results of applying the Tukey Method[11] of multiple comparisons in pairs to the mean values for the twelve operators for each of the

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[9] Snedecor, G. W., Statistical Methods Applied to Experiments in Agriculture and Biology, The Iowa State College Press, Ames, Iowa, 1946, chapter 11.

[10] Brownlee, K. A., Industrial Experimentation, Chemical Publishing Company, Brooklyn, 1948, p. 55.

[11] Tukey, J. W., "Comparing Individual Means In The Analysis of Variance," Biometrika, 1949, volume 5, pp. 99-114.

six transports under the three different setups. The procedures used in making the multiple comparisons are set forth in Appendix D.

Table 20 of Appendix D gives the rank order of the means for all twelve operators for the transports T_2, T_3, T_5, and T_6.

Table 1

Data for Operator 1

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	234	168	219	201	182	178
2	161	163	206.5	169.5	158	184
3	156	174	194	181.5	167	168
4	218	170.5	202.5	193.5	147	153
5	175	159	183	205	159.5	180
6	207	166	198	209	160	163
7	149	162	183	201	162.5	168
8	132	191.5	191	209.5	150	172
9	162	163	199	197	159	164
10	176	184	167.5	158	152	172
	Setup B					
1	159	155	187	186.5	148	153.5
2	142.5	161.5	166.5	162.5	145	155
3	162	164.5	170	163	154	147
4	143.5	167	183	167	144.5	149
5	126.5	158.5	170	175	149	137
6	138.5	163.5	178	174	156	162
7	163	169.5	174	152	165	166
8	167	182	163	194.5	141.5	147.5
9	174.5	172	177.5	203	156	151
10	135	178	190	180	183	173
	Setup C					
1	243	266.5	186.5	173.5	191	180
2	159	218	195	169	176	192
3	164	197.5	183	178.5	166.5	163
4	144	183	175	161	168	164
5	160	173	157	177.5	166.5	163.5
6	133.5	199.5	182	167	167	176
7	129	174	179	170	160	163.5
8	175	194	179	150	163	165
9	155	182	183	181.5	157	164
10	193	189.5	183	177	170	177.5

Table 2

Data for Operator 2

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	151	120.5	201.5	174	118	142
2	176.5	123.5	221	147	126	167
3	156	119.5	234	167.5	129	199.5
4	198	122	186	166	141	208
5	133.5	116.5	205.5	150	121	148.5
6	147.5	120	202	149	131	156.5
7	139	103	199	158	120	171.5
8	151	112	161.5	154	137	146.5
9	136	112.5	194	143	127	173
10	148	113.5	230	153.5	121	180.5
	Setup B					
1	218	130.5	171	150	117.5	134
2	132.5	115	195	166	126.5	141.5
3	152.5	126.5	213	151.5	133.5	158
4	149.5	130	225	201.5	156	168
5	151.5	162.5	183	143.5	147	153
6	132	127	183	150	158	173
7	152	170	167	146.5	136	148.5
8	151.5	138.5	205.5	154	130.5	157
9	148	131.5	188.5	146	140	157
10	148.5	138	175	158	154	193.5
	Setup C					
1	154	106.5	152	144	150.5	167.5
2	147.5	123	174.5	143	132	181
3	147	115	171	142	141	161
4	148	114.5	154	145.5	120	141
5	143	164	120	142	152	138.5
6	137	140	132	162	137.5	157
7	137.5	113	136	146	159	133.5
8	132	116.5	131.5	131	143	144
9	140.5	108.5	167	150.5	141	173.5
10	144	115	171	143.5	139.5	148

Table 3

Data for Operator 3

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	195.5	123	155	163	124	141.5
2	145.5	123.5	163.5	138	120	149
3	141	128	178.5	147	120	152
4	152	117.5	159	143	127	140
5	139.5	125	155.5	142.5	123	142
6	145	115	156	143.5	119	148
7	141	128	147.5	150	122	136
8	136	119.5	158.5	139.5	121	167.5
9	151.5	117	155.5	135	122	149
10	137.5	119	171	142	112	155.5
	Setup B					
1	191.5	143	174	171.5	152	164.5
2	157	147	163	162	147	161
3	150.5	166.5	162.5	158	133.5	144.5
4	149	134.5	147.5	146.5	142.5	157
5	144.5	147	159	151.5	148.5	154
6	159	140	174	166.5	149	163.5
7	163	154.5	159.5	154.5	142	158
8	148.5	141	156.5	142	148	152
9	152	140	171.5	148	135	147.5
10	152.5	143.5	169.5	142.5	145.5	156.5
	Setup C					
1	238.5	166.5	195	178	146.5	175.5
2	151.5	151	190.5	150.5	144	182.5
3	152	151	178	154	141.5	166
4	145.5	163	175	162.5	151	169
5	137	165	170	150	144	168.5
6	139.5	155.5	178	158.5	157	156
7	145	158.5	174	163	144.5	163
8	149.5	159	167	144	141.5	161
9	142	157.5	166.5	142.5	129	156.5
10	152	153	166.5	155	139	171.5

Table 4

Data for Operator 4

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	181	110	131	137	143	141
2	105	111	138.5	132.5	116	107
3	107	113.5	139	131	121	122
4	102.5	108	120	132	116.5	113
5	119	116	128	121	116	114
6	133	120	129	128	129	112
7	115	116	140.5	128	129	117
8	110.5	104	128	115	110	105.5
9	116.5	112.5	124	121	121	111.5
10	110	105	128	144	120.5	99.5
	Setup B					
1	155.5	111.5	299.5	135	125.5	127.5
2	115	120	144.5	124	124.5	128
3	114	120	140	131	126	125
4	118	124	133	130	130	120
5	121	129	136	145	136.5	125.5
6	110	127	136	115.5	155	129
7	139	142	127.5	127	127	121.5
8	115	142	133	127.5	149.5	132
9	106	132	131	131	146	114
10	106	134	143	116	135.5	127
	Setup C					
1	170	151	145.5	156.5	163	136
2	149	132	159	154	138	136
3	125	126	136	144	136.5	117.5
4	119	151	135	134.5	163	122
5	127	141	124.5	139.5	140	122
6	116	143	131.5	130	137.5	125
7	118	151	140	119	133.5	139
8	134	135.5	120	115	135	128.5
9	129.5	150.5	136	122.5	132	132
10	122	141	140	122	146.5	120

Table 5

Data for Operator 5

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	250	156	187	208.5	144	196
2	168	144	190	183	145	177.5
3	170.5	146	186	181.5	142	175
4	178.5	151.5	186.5	193	157	191
5	175	155	210.5	186	156.5	167.5
6	181	143	210	187	134	175.5
7	174.5	154	203	169	136	171
8	182	144	194.5	197	143	157
9	154	148	195	189	144	176
10	160	133	194	182	125	172.5
	Setup B					
1	258	152	194	177.5	160.5	177
2	151	156.5	167	143	160.5	168
3	148	144.5	185	185.5	152.5	176
4	158.5	141.5	179	181	147.5	168.5
5	148.5	144	175	193	143	173
6	152	167	176.5	181.5	146.5	158
7	147.5	161	176	166.5	143	163.5
8	168	153.5	174	176	146.5	149
9	160.5	158	180.5	173	141	160
10	157	166	234	177.5	146	165
	Setup C					
1	226.5	143	146.5	182	156	180.5
2	168	128.5	159.5	170	215	182
3	156	143.5	178.5	174.5	160.5	160.5
4	159.5	167	153	193.5	164.5	176
5	155.5	178	169.5	156	153	190
6	152	163	172	178	157	172
7	167.5	163.5	173	178	152.5	175
8	160	151	179	170.5	172	160.5
9	187	159	149	178.5	163	187.5
10	158	147.5	167	178.5	160.5	218

Table 6

Data for Operator 6

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	183	164.5	191	183	138	140.5
2	185	149.5	171.5	142	139	131.5
3	172.5	154	160	161.5	150.5	124
4	172	149	155.5	143	145	132.5
5	175.5	148	154	158.5	147	129
6	169	164	144	162	135	149
7	145.5	154.5	167	161.5	145	125
8	169	138	159	166.5	140	129
9	159	140	167	153	141.5	145
10	153	145.5	159	158.5	145	158
	Setup B					
1	189	192	168	172.5	145	167
2	181	168.5	154	185	136	116
3	173	173	152	160	137	143
4	168	162	149	157.5	144	147.5
5	160.5	141.5	186	182	156.5	125
6	153	154.5	137	154.5	148	147
7	168	161	134	173.5	132	117.5
8	167	143	157.5	165.5	148	153
9	161	152	172.5	167	144	171
10	163.5	150	160.5	178	155	146.5
	Setup C					
1	196	185	167	183.5	146	135
2	154	156.5	156	165	137	129
3	154	151.5	147	165	156	136
4	141.5	165	163.5	142	132	158.5
5	154	150.5	144	166	144	132
6	138	160.5	164	161	139	134
7	148.5	159	136	165	149	122.5
8	137	150	166.5	154.5	147.5	148
9	141	161	152	146.5	145	129
10	145	168.5	145	157.5	153	127.5

Table 7

Data for Operator 7

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	264	152	210	189	129.5	178.5
2	173	181.5	202.5	179.5	147.5	195
3	193	157.5	207	191	124.5	166
4	170.5	156	201.5	189.5	120	176.5
5	184.5	161	198	200.5	116	161.5
6	180	154	210.5	201	121	190
7	172.5	157	211	184	140.5	162.5
8	195	149	191	208	128	168
9	192	138.5	195	188.5	116	149.5
10	199.5	142	202.5	197.5	132.5	183.5
	Setup B					
1	174	175.5	168	162.5	145.5	145
2	158	160	165	163	130	138.5
3	161.5	141	176	189	139.5	140
4	153.5	146.5	168	152	132	142.5
5	165.5	154	164	185.5	129	157
6	177	141	163.5	189.5	145.5	147
7	192	142	160.5	174	137	155
8	177.5	146	164	162	129.5	151
9	150	148	171	166.5	128	155
10	162	147	165	171	136	147
	Setup C					
1	191.5	140.5	183	189	143.5	183
2	166	177	187	197	141	155.5
3	176.5	163.5	198.5	197	136	170
4	166	152	178	196.5	131	156
5	176	136.5	156	212.5	128.5	162
6	150	141.5	163.5	188	135	150
7	153	145	144	189	128.5	178
8	164	138.5	144.5	172.5	140	151
9	150	159.5	145	178.5	135.5	178.5
10	169	154.5	153	173.5	139.5	160

Table 8

Data for Operator 8

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	228	169.5	183	187	161	144.5
2	151	164.5	155	180.5	161	128
3	130.5	160.5	156	228	156.5	148
4	150	161	155.5	166	153	136.5
5	154	137.5	152	156	148.5	131
6	141.5	142	168	186	153	160.5
7	146	148.5	144	170	142.5	143
8	158	160.5	155.5	160	137	144.5
9	154.5	142	172.5	174	156	143.5
10	161	167	183	146	148	190
	Setup B					
1	200	186	205.5	173	172	168
2	173.5	177	190	209	189.5	148
3	195.5	185	167	186.5	177	156
4	196	198.5	191	189.5	188	157.5
5	200.5	197	214	182.5	182	171
6	184.5	190.5	191	189	181	167
7	232	195	226	216	208	176
8	184.5	183.5	187.5	264	183.5	200
9	180.5	215	191	198.5	197	158
10	184	199	196.5	184.5	187.5	173
	Setup C					
1	243	148.5	183	170	188.5	160
2	166	155.5	171	142	180	134.5
3	130	145.5	164	158	174	143.5
4	123	171	188	139.5	176.5	155
5	156.5	163	187	158	172	152
6	141.5	192	185	154.5	187.5	150
7	158	187.5	186.5	158	184	151
8	161.5	195	216	174	177	183
9	158	202	194.5	154	211	159
10	150.5	204	171.5	150	182.5	201.5

Table 9

Data for Operator 9

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	194.5	140.5	209	177.5	144	169.5
2	143	145	206.5	185	146	164
3	159	147.5	201.5	166.5	135	169.5
4	171	144.5	191	174	142.5	170.5
5	156.5	141	194	177	146.5	168
6	166	143.5	187	181.5	141	150.5
7	168	147	202	174.5	140	165.5
8	167.5	140	179	170.5	139	158
9	162	132.5	182.5	174	146	161
10	150	140.5	183.5	174.5	135	151
	Setup B					
1	202.5	143	188	157.5	153	145.5
2	154	138.5	191	155.5	154	157
3	148	144.5	202.5	162	151	147
4	150	147	183.5	193.5	173	150.5
5	156.5	147.5	183.5	183	173.5	159
6	158	145	190	189	157.5	170
7	159	148	187	201.5	147	174
8	167	138	217.5	154.5	156.5	153.5
9	151	139	221	187	158	188.5
10	169	148.5	194.5	174	161.5	156.5
	Setup C					
1	202	150	195	195	168	177
2	136	156	171.5	178.5	165	201
3	151	145	214	168	167	191
4	158	165	199.5	166.5	170	166
5	154	171	155	166	176.5	184.5
6	162	170	183	162	171	154.5
7	132	165	178.5	154	156.5	155.5
8	167	159.5	214.5	177	172.5	162
9	143	163	167	148	176.5	177.5
10	142	171	171.5	158.5	168	158

Table 10

Data for Operator 10

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	198.5	150	189	178	157	166
2	161	150	198	196	137	180
3	159	143.5	190.5	190	143.5	154
4	164	161.5	186	209	142	154
5	192	177.5	190	182	150	174
6	182	161.5	187	205	141	156.5
7	181.5	164	175	209	146.5	162
8	162.5	170	193.5	205	156	158
9	171	151.5	174.5	186	173	150
10	162.5	163	210.5	197.5	146.5	165
	Setup B					
1	203	178	167	190	164.5	157
2	157	162	182	181.5	156	151
3	178	161.5	230	190	161	174
4	192	175	182	182	167	147
5	166.5	166.5	203	189	148.5	151
6	185.5	174	183	182	147	193
7	193	170.5	201	212.5	156	158.5
8	175	158.5	196.5	188	152	183.5
9	204	146	188.5	170	157	150.5
10	154	156	182.5	210	163	165
	Setup C					
1	267	153.5	223	201	162.5	178
2	218	208.5	229	232.5	156.5	213
3	197	194	209.5	228	173	199.5
4	202	174	225	225.5	173	203.5
5	221	170	198	206	178	173
6	231.5	178	211	202	174	182.5
7	206	191	218	210	178	182
8	198.5	193.5	221	206	169	204
9	196.5	196	222	235	170	190
10	218	199	206	183	170	191

Table 11

Data for Operator 11

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
			Setup A			
1	217	162.5	214	181.5	146.5	165.5
2	183	166	196.5	152	165.5	143.5
3	158	160.5	179.5	169	147.5	160
4	169.5	173	184.5	164	163	166
5	181	165.5	188	177.5	155	152
6	170	165	171	178	170	144
7	170	154.5	173	174	155.5	170
8	170.5	151	172	185	148.5	161
9	143	162	176	166	152	140
10	143	147	188	175	149	169
			Setup B			
1	131	146	180	208	161.5	143
2	155	140	172.5	166.5	164	139
3	144	135	202	193	145	146
4	147	165.5	171	163.5	151	140.5
5	158.5	153.5	179.5	146	155	149.5
6	142.5	150	156	147	146.5	177.5
7	146	158	167	150.5	140	150.5
8	147	139	183	196	146	150.5
9	129	145.5	173	167.5	154	154
10	143	157	175	162	158	140.5
			Setup C			
1	199	174.5	233	177.5	142.5	174
2	162.5	181	185.5	177.5	167	164
3	166	182	190	169	166	172
4	156	167	182.5	185	162	161
5	150	166	194	198.5	160	162
6	164.5	155	183	168	154	190
7	159	164	191	177	161	166
8	148	162	226	162	161.5	165.5
9	154.5	180.5	195	178	163	171.5
10	190	160	185	158	166	177

Table 12

Data for Operator 12

Cycle	T_1	T_2	T_3	T_4	T_5	T_6
	Setup A					
1	240	177.5	221	204.5	151	181.5
2	213	169	225.5	206.5	162	182.5
3	170	165	245	201	171	188.5
4	186	157.5	210.5	181	150	186
5	217.5	181	215	178.5	163	174.5
6	170.5	155	230	213	144	177.5
7	186	154	214	202	149	177
8	174.5	157.5	180.5	174	143.5	193
9	182	166	223	205	154	158
10	190	170	210	180.5	160.5	192
	Setup B					
1	271.5	196.5	211	208	174	209
2	181	202.5	209.5	181	168	197
3	177	193	212	192.5	157.5	190
4	173	166	215	178	167	177.5
5	177.5	193	227.5	200	157	162
6	178	152.5	203	205	167	185
7	162	165	197	177.5	181	216.5
8	166.5	181.5	197.5	187	155	197
9	183	185	210	193	141.5	189
10	154	189	219	185	164	161
	Setup C					
1	275	201	224	196.5	178	228
2	181.5	183	210	206	180	220
3	174	173.5	195.5	197	174.5	206
4	189.5	193.5	195	181	165	197.5
5	182	179	210	168	162	192
6	177	181	191	183	157	197
7	182	165.5	196	189.5	174	170
8	165.5	173	191	177.5	162	165
9	146.5	159	191	185	159.5	193
10	162	170.5	174.5	167	163.5	190

Table 13

Mean Value of Transports For All 12 Operators

Setup	T_1	T_2	T_3	T_4	T_5	T_6
A	166.5	146.3	183.1	173.0	141.3	158.1
B	162.6	156.3	180.0	171.4	151.7	156.5
C	163.3	163.2	175.7	168.9	157.8	165.8

DISCUSSION OF RESULTS

The Analysis of Variance (Table 15 of Appendix B) revealed the following facts:

1. The time values obtained for the transports T_1 and T_4 under the three experimental setups were not significantly different.
2. The time values obtained for the transports T_2, T_3, T_5 and T_6 under the three experimental setups were significantly different at the one percent level.
3. Even though no significant differences were obtained for the transports T_1 and T_4, there were differences among the operators which were significant at the one percent level. The interaction of operators versus setups was also significant at the one percent level.
4. For the transports T_2, T_3, T_5, and T_6, the operator differences and the interaction of operators versus setups were significant at the one percent level.

The computation of the components of variation (Table 17 of Appendix C) revealed the following facts:

1. The percentage of the total variation which could be attributed to the error of measurement was 23.5% for T_2, 33.3% for T_3, 23.1% for T_5, and

23.5% for T_6.

2. The percentage of the total variation which could be assigned to the interaction of operators versus setups was 13.3% for T_2, 24.0% for T_3, 9.4% for T_5, and 11.1% for T_6.
3. The percentage of the total variation due to the change in setups was 11.7% for T_2, 1.5% for T_3, 18.9% for T_5, and 4.3% for T_6.
4. The percentage of the total variation due to the operators was 51.4% for T_2, 41.2% for T_3, 48.5% for T_5, and 52.1% for T_6.

The multiple comparisons of the means established the following facts:

1. The means for T_2 and T_5 under the three experiment setups were significantly different and could be ranked in order of magnitude.
2. For T_3, the means of setups A and C were significantly different, but the mean of setup B was not significantly different from that of either setup A or setup C.
3. For T_6, the means of setups A and B were not significantly different, but the mean of setup C was significantly different from the means of both other setups.

Table 20 of Appendix D shows the rank order assigned to the means of T_2, T_5, and T_6, and the two possible rankings

of the means of T_3. The means were ranked as follows:

1. For T_2, setup A required the least time, setup B was second, and setup C required the greatest time.
2. For T_3, setup C required the least time, setup B was indeterminate in that it could be equal to setup A or setup C, and setup A required the greatest time.
3. For T_5, setup A required the least time, setup B was second, and setup C required the greatest time.
4. For T_6, setups A and B were essentially equal and required the least time, and setup C required the greatest time.

The evidence from the analysis of variance supports the hypothesis that therblig times were inter-related. While it is true that T_1 and T_4 were apparently not affected by the change in therblig sequence, it is thought that several possible patterns are available.

The possible explanations are proposed below:

1. T_1 and T_4 were alike in that each was a transport empty and each occurred in the cycle before any change took place in the therblig sequence. This possibility involves the assumption that the momentary pause and change of direction at station 1 made, in effect, a separate cycle out of the

reverse motion path.

2. T_1 and T_4 were also alike in that each was a motion which was made in a direction away from the operator.

Of the two possible explanations offered above, it is felt that the former is more plausible, however, additional evidence is needed before either could be adopted or discarded.

T_3 and T_6 were each a transport empty which followed a change in the therblig sequence. They were also alike in that each was a motion which was made in a direction toward the operator. The fact that T_3 and T_6 were affected by the change in therblig sequence does not appear to be inconsistent with the fact that T_1 and T_4 were not affected.

T_2 and T_5 were each a transport loaded. T_2 preceded the change in therblig sequence while T_5 followed the change. The additional time required for T_2 under setups B and C is thought to be due to the anticipation of the increased difficulty of the more precise positioning of the load. The additional time required for T_5 under setups B and C must be attributed to the increased difficulty of the disassemble which immediately preceded the transport loaded.

The manner in which the mean value of the transports (Table 20 of Appendix D) varied under the three setups is interesting to note. T_2 varied directly with the difficulty

which was presumed to be designed into the interchangeable devices located at station 3. As discussed above, this is thought to be caused by anticipation of the increased requirements. T_3 was not affected by the change in therblig sequence as much as T_2 was since only the extremes (setups A and C) were significantly different. The extremes (setups A and C) varied inversely with the designed difficulty of the preceding requirements. Three possible explanations are offered:

1. The designed difficulty of setup B was not actually different from that of setup A or C as far as T_3 was concerned.
2. Considering the extremes (setups A and C), the operators sensed that they were behind and speeded up the next motion.
3. The conclusion of Schwab,[12] that therblig times do not vary in a set pattern from one level of activity to another, suggests that therblig times affected by a change in therblig sequence would not vary in a set pattern.

Again, additional evidence is needed before a conclusion could be stated.

To apply the line of reasoning used on T_3 above to T_5 might appear to be inconsistent as T_5 varied directly with

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[12]Schwab, op.cit.

the designed difficulty of the preceding therblig. T_5 showed that the designed difficulty of setup B was sufficiently different from setups A and C to cause a significant difference in time required. The only explanation which can be offered is that a transport loaded therblig and a transport empty therblig are affected differently by a change in therblig sequence.

The manner in which T_6 varied, since T_6 was a transport empty therblig, can only be explained by reference to the third possible explanation offered for T_3.

It would seem important to have a logical explanation for the observed variations, however, it is thought to be more important that the variations do occur.

The percentage of the total variation (Table 17 of Appendix C) which was assigned to a particular source of variation is of interest as T_3 and T_6 had rather small percentages which were attributed solely to the change in setups. The important fact, however, is that the differences among setups were significant for the transports T_2, T_3, T_5, and T_6.

The percentage of the total variation assigned to the operators certainly bears out the accepted concept of individual differences.

CONCLUSIONS

For the operators who participated in the experiment and under the conditions which prevailed, the following conclusions can be stated:

1. The evidence obtained as the result of this experiment supports the hypothesis that time values for certain therbligs (transport empty and transport loaded) cannot be given as universal values since they are affected by other therbligs in the motion sequence.
2. Several causative factors were suggested, but more evidence is needed to assign a reason for the observed variation.

A P P E N D I X   A

MISCELLANEOUS FIGURES

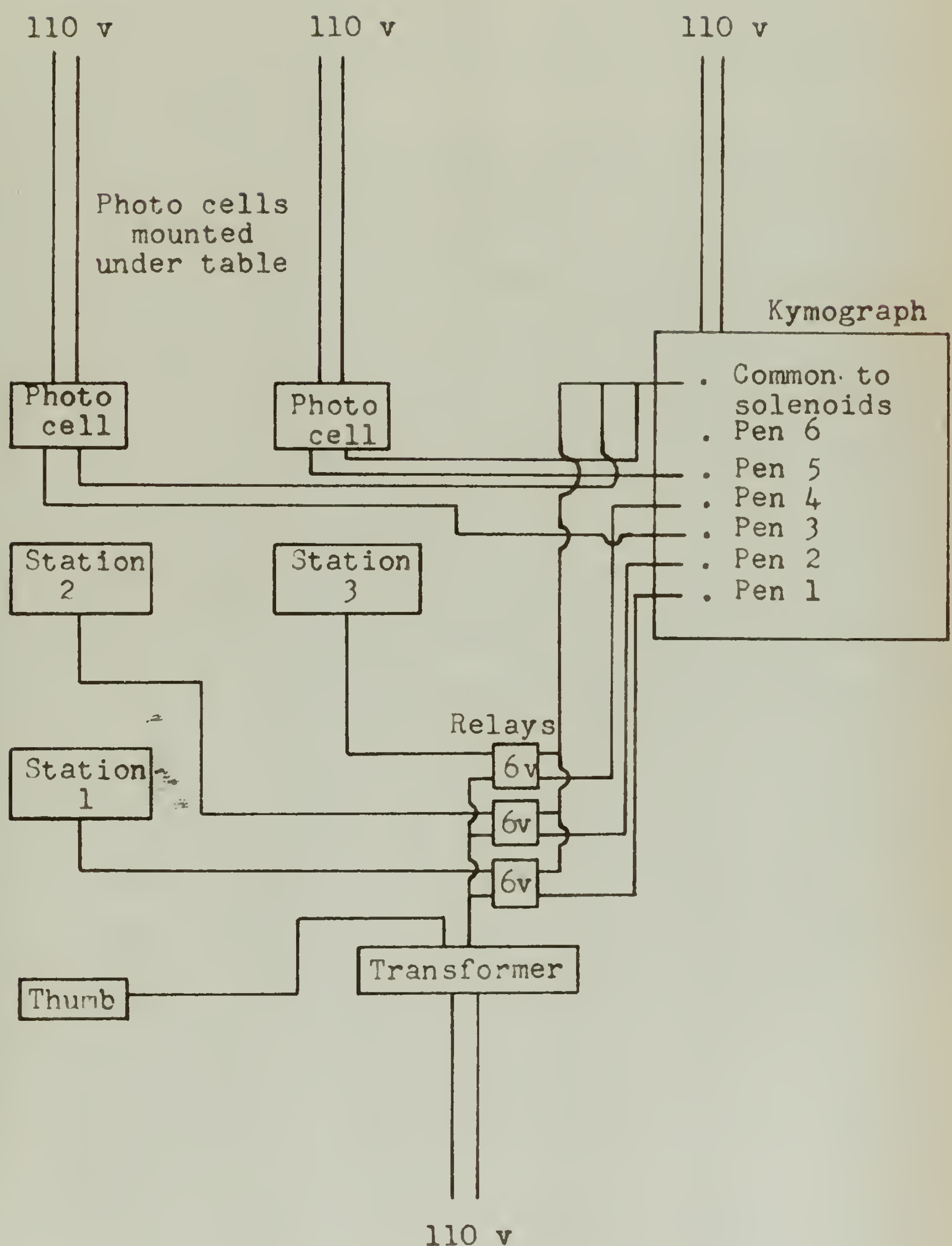

Fig. 7 Wiring Diagram

Instructions for Operators

1. The experiment in which you are about to take part consists of performing three setups of a simple task with your right hand.
2. The motion path and therbligs involved in the three setups are essentially the same and are as follows:
   a. Contact grasp front of plate at station 1.
   b. Transport empty from station 1 to station 2.
   c. Grasp the cube at station 2 by placing the thumb on the near side of the cube and the first three fingers on the opposite side.
   d. Transport loaded from station 2 to station 3.
   e. Position cube and assemble as required at station 3. Do not drop cube--place firmly on surface before releasing.
   f. Release load cube at station 3.
   g. Transport empty from station 3 to station 1.
   h. Contact grasp front of plate at station 1 with thumb.
   i. Transport empty from station 1 to station 3.
   j. Grasp cube at station 3.
   k. Disassemble as required at station 3 and transport loaded to station 2.
   l. Position and release load cube at station 2. Do not drop cube--place firmly on surface before releasing.

Fig. 8-1

m. Transport empty from station 2 to station 1.

n. Contact grasp front of plate at station 1 with thumb.

3. A recorded run will be taken for each setup of the task and will consist of ten cycles as described above.

4. Work as rapidly as you can.

5. You will have about five minutes rest between recorded runs to enable the final preparations for the next run to be completed.

Fig. 8-2

Order of Presentation of Experiment Setups

Operator	First	Second	Third
1	A	B	C
2	B	C	A
3	C	A	B
4	C	B	A
5	B	A	C
6	A	C	B
7	A	B	C
8	B	C	A
9	C	A	B
10	C	B	A
11	B	A	C
12	A	C	B

The letter in the cell is the setup designator.

For ease of reference they are repeated below.

Setup	Device at station 3
A	4" circular container
B	2-1/4" square container
C	plate with two 1/2" dowels

Fig. 9

APPENDIX B

Analysis of Variance

The analysis of variance was completed as outlined below. The calculations in this example were based on the data obtained for T_2. The analysis used was a factorial design with replication. The setups were arranged in columns, the operators in rows, and there were ten measurements in each cell (Table 14).

1. Computation of Q_e, the within cell variation.

$$Q_e = \sum_{1}^{N} X^2 - \frac{\sum_{1}^{km} T_i^{\,2}}{v}$$

Where X = an individual measurement,

N = total number of measurements,

k = the number of columns,

m = the number of rows,

T_i = the total of all measurements in a cell, and

v = the number of measurements in a cell.

$$Q_e = \sum_{1}^{360} X^2 - \frac{\sum_{1}^{36} T_i^{\,2}}{10}$$

$$Q_e = 8,867,356.75 - 8,821,112.375 = 46,244.375$$

Table 14 - 1

Factorial Design With Replication

	Setup A		Setup B		Setup C	
Operator 1	168 163 174 170.5 159	166 162 191.5 163 184	155 161.5 164.5 167 158.5	163.5 169.5 182 172 178	266.5 218 197.5 183 173	199.5 174 194 182 189.5
Operator 2	120.5 123.5 119.5 122 116.5	120 103 112 112.5 113.5	130.5 115 126.5 130 162.5	127 170 138.5 131.5 138	106.5 123 115 114.5 164	140 113 116.5 108.5 115
Operator 3	123 123.5 128 117.5 125	115 128 119.5 117 119	143 147 156.5 134.5 147	140 154.5 141 140 143.5	166.5 151 151 163 165	155.5 158.5 159 167.5 163
Operator 4	110 111 113.5 108 116	120 116 104 112.5 105	111.5 120 120 124 129	127 142 142 132 134	151 132 126 151 141	143 151 135.5 150.5 141
Operator 5	156 144 146 151.5 155	143 154 144 148 133	152 156.5 144.5 141.5 144	167 161 153.5 158 166	143 128.5 143.5 167 178	163 163.5 151 159 147.5
Operator 6	164.5 149.5 154 149 148	164 154.5 138 140 145.5	192 168.5 173 162 141.5	154.5 161 143 152 150	185 156.5 151.5 165 150.5	160.5 159 150 161 168.5

Table 14 - 2

Factorial Design With Replication

	Setup A		Setup B		Setup C	
Operator 7	152 181.5 157.5 156 161	154 157 149 138.5 142	175.5 160 141 146.5 154	141 142 146 148 147	140.5 177 163.5 152. 136.5	141.5 145 138.5 159.5 154.5
Operator 8	169.5 164.5 160.5 161 137.5	142 148.5 160.5 142 167	186 177 185 198.5 197	190.5 195 183.5 215 199	148.5 155.5 145.5 171 163	192 187.5 195 202 204
Operator 9	140.5 145 147.5 144.5 141	143.5 147 140 132.5 140.5	143 138.5 144.5 147 147.5	145 148 138 139 148.5	150 156 145 165 171	170 165 159.5 163 171
Operator 10	150 150 143.5 161.5 177.5	161.5 164 170 151.5 163	178 162 161.5 175 166.5	174 170.5 158.5 146 156	153.5 208.5 194 174 170	178 191 193.5 196 199
Operator 11	162.5 166 160.5 173 165.5	165 154.5 151 162 147	146 140 135 165.5 153.5	150 158 139 145.5 157	174.5 181 182 167 166	155 164 162 180.5 160
Operator 12	177.5 169 165 157.5 181	155 154 157.5 166 170	196.5 202.5 193 166 193	162.5 165 181.5 185 189	201 183 173.5 193.5 179	181 165.5 173 159 170.5

2. Computation of $Q_{c,r}$, the among cell variation.

$$Q_{c,r} = \frac{\sum_{1}^{km} T_i^{\,2}}{v} - \frac{T^2}{N}$$

Where T = the total of all measurements

$$Q_{c,r} = \frac{\sum_{1}^{36} T_i^{\,2}}{10} - \frac{T^2}{360}$$

$$Q_{c,r} = 8,821,112.375 - 8,678,319.806 = 142,792.569$$

3. Computation of Q_c, the column to column variation.

$$Q_c = \frac{\sum_{1}^{k} T_c^{\,2}}{mv} - \frac{T^2}{N}$$

Where T_c = the total of a column.

$$Q_c = \frac{\sum_{1}^{3} T_c^{\,2}}{120} - \frac{T^2}{360}$$

$$Q_c = 8,695,701.885 - 8,678,319.806 = 17,382.079$$

4. Computation of Q_r, the row to row variation.

$$Q_r = \frac{\sum_{1}^{m} T_r^{\,2}}{kv} - \frac{T^2}{N}$$

Where T_r = the total of a row.

$$Q_r = \frac{\sum_{1}^{12} T_r^{\,2}}{30} - \frac{T^2}{360}$$

$$Q_r = 8,782,804.142 - 8,678,319.806 = 104,484.336$$

5. Computation of Q_{cxr}, the variation due to the interaction among rows and columns.

$$Q_{cxr} = Q_{c,r} - Q_c - Q_r$$

$$Q_{cxr} = 142{,}792.569 - 17{,}382.079 - 104{,}484.336$$
$$= 20{,}926.154$$

6. Computation of mean squares for the sources of variation.

$$\text{Mean square} = \frac{\text{Sum of squares}}{\text{Degrees of freedom}}$$

Source of Variation	Degrees of Freedom, d.f.	Sum of Squares, Q	Mean Square, $\frac{Q}{d.f.}$
Among Setups	2	17,382.079	8,691.0395
Among Operators	11	104,484.336	9,498.576
Operator x Setup Interaction	22	20,926.154	951.1888
Error	324	46,244.375	142.7296

7. Computation of the F_c values for the sources of variation.

The F_c values for the sources of variation were obtained by determining the ratio between the mean square of the source of variation and the mean square of the error term.

8. Comparison of the computed F values with tabulated

F values.

The F values were obtained from Snedecor.[13] To locate the appropriate F value, the table was entered with the degrees of freedom of the source of variation, the greater mean square, and the degrees of freedom of the error term, the lesser mean square. Table 15 shows the comparison of the computed F values with the tabulated F values.

The intermediate data for the transports, T_1 through T_6, is recorded in Table 16.

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[13] Snedecor, *op. cit.*, pp. 222-5.

Table 15

Comparison of Computed F With Tabulated F Values

Transport	Among Columns (Setups) [2,324]			Among Rows (Operators) [11,324]			Interaction (Setups x Operators) [22,324]		
	F_c	$F_{.01}$	Significant at .01 level	F_c	$F_{.01}$	Significant at .01 level	F_c	$F_{.01}$	Significant at .01 level
T_1	1.10	4.68	No	18.74	2.31	Yes	3.14	1.90	Yes
T_2	60.89	4.68	Yes	66.55	2.31	Yes	6.66	1.90	Yes
T_3	6.38	4.68	Yes	38.15	2.31	Yes	8.23	1.90	Yes
T_4	2.82	4.68	No	60.89	2.31	Yes	5.39	1.90	Yes
T_5	99.53	4.68	Yes	63.99	2.31	Yes	5.04	1.90	Yes
T_6	17.00	4.68	Yes	49.09	2.31	Yes	4.40	1.90	Yes

Table 16 - 1

Intermediate Data For Analysis of Variance

		T_1	T_2	T_3	T_4	T_5	T_6
Total ΣX		59,085.0	55,894.5	64,646.5	61,594.5	54,083.0	57,646.0
Total ΣX^2		9,988,226.50	8,867,356.75	11,851,964.75	10,738,055.25	8,237,024.0	9,402.886.0
Sums by Setups	A	19,982.0	17,552.5	21,969.0	20,758.0	16,952.5	18,969.5
	B	19,509.0	18,759.0	21,596.0	20,566.5	18,199.5	18,783.5
	C	19,594.0	19,583.0	21,081.5	20,270.0	18,931.0	19,893.0
Sums by Operator	1	4,937.0	5,349.5	5,505.0	5,387.5	4,824.0	4,951.5
	2	4,503.0	3,748.5	5,449.5	4,578.5	4,085.5	4,821.5
	3	4,614.5	4,272.5	4,997.5	4,544.5	4,091.0	4,708.5
	4	3,708.5	3,819.5	4,197.0	3,908.5	4,002.5	3,670.0
	5	5,132.5	4,562.5	5,444.5	5,390.0	4,567.5	5,219.0
	6	4,876.5	4,712.0	4,739.5	4,891.0	4,320.0	4,148.5
	7	5,257.0	4,558.0	5,346.5	5,537.0	3,986.0	4,853.0
	8	5,093.5	5,243.5	5,430.5	5,304.0	5,215.0	4,733.5
	9	4,819.5	4,476.5	5,744.0	5,186.0	4,691.0	4,956.0
	10	5,697.5	5,098.0	5,972.0	5,981.5	4,768.5	5,166.5
	11	4,857.5	4,788.5	5,566.5	5,182.5	4,676.5	4,765.0
	12	5,588.0	5,265.5	6,254.0	5,703.5	4,855.5	5,653.0

Table 16 - 2

Intermediate Data For Analysis of Variance

	T_1	T_2	T_3	T_4	T_5	T_6
$\frac{(T.\Sigma X)^2}{360}$	9,697,325.63	8,678,319.81	11,608.805.45	10,538,562.31	8,124,919.14	9,230,725.88
Total S. S.	290,900.88	189,036.94	243,159.30	199,492.94	112,104.86	172,160.12
$Q_{c,r}$	134,193.93	142,792.57	159,114.82	141,673.52	84,955.66	116,093.52
Q_e	156,705.95	46,244.38	84,044.48	57,819.43	27,149.20	56,066.60
Q_c	1,059.72	17,382.08	3,309.71	1,007.58	16,679.34	5,884.55
Q_r	99,684.28	104,484.34	108,843.94	119,524.15	58,982.78	93,441.57
Q_{cxr}	33,449.93	20,926.15	46,961.17	21,141.79	9,293.57	16,767.40
$Q_c/2$	529.86	8,691.04	1,654.85	503.79	8,339.67	2,942.28
$Q_r/11$	9,062.21	9,498.58	9,894.90	10,865.83	5,362.07	8,494.69
$Q_{cxr}/22$	1,520.45	951.19	2,134.60	960.99	422.44	762.15
$Q_e/324$	483.66	142.73	259.39	178.46	83.79	173.05

APPENDIX C

Computation of Components of Variation

Table 16 of Appendix B records the mean square values for the sources of variation as obtained by the analysis of variance. For use as an example a part of Table 16 is reproduced below. The data are for the transport T_2.

Source of Variation	Sum of squares	Mean square
Among operators	104,484.3	9,498.6
Among setups	17,382.1	8,691.0
O X S Interaction	20,926.2	951.2
Residual or error	46,244.4	142.7

The expected mean squares for the sources of variation are given below.

Source of variation	Expected mean square
Among operators	$\sigma_e^2 + 10\left[\frac{K-k}{K}\right]\sigma_I^2 + 10k\,\sigma_o^2$
Among setups	$\sigma_e^2 + 10\left[\frac{M-m}{M}\right]\sigma_I^2 + 10m\,\sigma_s^2$
O X S Interaction	$\sigma_e^2 + 10\sigma_I^2$
Residual or error	σ_e^2

Where σ_e^2 = the variation due to error,

σ_I^2 = the variation due to the interaction,

σ_s^2 = the variation due to setups,

σ_o^2 = the variation due to operators,

m = the number of setups,

M = the total population of setups,

k = the number of operators, and

K = the total population of operators.

Treating this experiment as a fixed model, m = M = 12 and k = K = 3, and the $\left[\frac{M-m}{M}\right]$ and $\left[\frac{K-k}{K}\right]$ terms reduced to zero. Substitution of the data for transport T_2 into the above equations for the expected mean squares gave the following results.

$$\sigma_e^2 = 142.7$$

$$\sigma_e^2 + 10\,\sigma_I^2 = 951.2$$

$$\sigma_I^2 = 80.9$$

$$\sigma_e^2 + 120\,\sigma_s^2 = 8691$$

$$\sigma_s^2 = 8548.3/120 = 71.2$$

$$\sigma_e^2 + 30\,\sigma_o^2 = 9498.6$$

$$\sigma_o^2 = 9355.9/30 = 311.9$$

The total variation was obtained by adding the components.

Total Variation = 142.7 + 80.9 + 71.2 + 311.9 = 606.7

The percentage of the total variation which could be attributed to a particular source of variation was determined by dividing the component of variation by the total variation.

$$\frac{142.7}{606.7} = 23.5\% \text{ of variation due to error}$$

$$\frac{80.9}{606.7} = 13.3\% \text{ of variation due to interaction}$$

$$\frac{71.2}{606.7} = 11.7\% \text{ of variation due to setups}$$

$$\frac{311.9}{606.7} = 51.4\% \text{ of variation due to operators}$$

Table 17 shows the results of the computation of components of variation. Transports T_1 and T_4 were not included since the analysis of variance showed that significant differences did not exist for these therbligs.

Table 17

Tabulation of Components of Variation

	T_2	T_3	T_5	T_6
σ_e^2	142.7	259.4	83.8	173.0
σ_I^2	80.9	187.5	33.9	58.9
σ_s^2	71.2	11.6	68.8	23.1
σ_o^2	311.9	321.2	175.9	277.4
Total variation	606.7	779.7	362.4	532.4
% due to σ_e^2 (error)	23.5	33.3	23.1	32.5
% due to σ_I^2 (interaction)	13.3	24.0	9.4	11.1
% due to σ_s^2 (setups)	11.7	1.5	18.9	4.3
% due to σ_o^2 (operators)	51.4	41.2	48.5	52.1
Total percentage	99.9	100.0	99.9	100.0

APPENDIX D

Multiple Comparisons of Means

The Tukey Method of multiple comparisons in pairs permitted the comparisons of the means of Setup A versus Setup B, Setup A versus Setup C, and Setup B versus Setup C to be handled as outlined below. Multiple comparisons were made only for the means of the transports for which the analysis of variance showed that significant differences existed. For use as an example a part of Table 13 is reproduced below. The data are for the transport T_2.

Setup	Mean Value of T_2 for 12 operators
A	146.3
B	156.3
C	163.2

To make the multiple comparisons it was necessary to check the θ confidence intervals which are

$$\theta \pm q\ (k,\ N-k) \sqrt{\frac{\sigma_e^2}{n}}$$

Where θ = the difference of the means being compared--i.e., $\theta = \bar{X}_A - \bar{X}_B$,

q = the studentized range,

k = the number of means in the experiment,

N = the total number of measurements in the experiment,

n = the measurements used in computing a single mean, and

σ_e^2 = the variation due to error.

In this case,

$k = 3, \quad N = 360, \text{ and } N - k = 357.$

To determine q, the studentized range, the table[14] was entered with k and N - k. For the 99% confidence level q (3,357) was found to be 4.12.

If $\theta \pm q\,(k, N\text{-}k)\sqrt{\dfrac{\sigma_e^2}{n}}$ does not overlap zero, a significant difference exists between the means being compared. The 99% confidence level means that the above statement will be true 99 times out of 100. A check of the θ confidence intervals of the data for T_2 was carried out as indicated below.

<u>Difference of means</u>

$$\bar{X}_A - \bar{X}_B = -10.0 = \theta_1$$

$$\bar{X}_A - \bar{X}_C = -16.9 = \theta_2$$

$$\bar{X}_B - \bar{X}_C = -6.9 = \theta_3$$

$$\sigma_e^2 = 142.7, \quad n = 120, \quad q(3,357) = 4.12$$

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[14] Dixon, W. J. and Massey, F. J., <u>Introduction to Statistical Analysis</u>, McGraw-Hill, New York, 1951, pp. 342-3.

$$(\theta_1): \ -10.0 \pm 4.12\sqrt{\frac{142.7}{120}}$$

$$= -10.0 \pm 4.12 \ (1.09)$$

$$= -10.0 \pm 4.49 = -5.51 \text{ to } -14.49$$

$$(\theta_2): \ -16.9 \pm 4.49 = -12.41 \text{ to } -21.39$$

$$(\theta_3): \ -6.9 \pm 4.49 = -2.41 \text{ to } -11.39$$

Since none of the θ confidence intervals overlapped zero it can be stated that a significant difference exists between the means compared, and the means can be ranked in order of magnitude. Table 18 records the intermediate data used in making the multiple comparisons, and Table 19 records the results of the multiple comparisons for T_2, T_3, T_5 and T_6.

Table 18

Data for Multiple Comparisons

Setup	$\bar{X}$ For All Operators T_2	T_3	T_5	T_6
A	146.3	183.1	141.3	158.1
B	156.3	180.0	151.7	156.5
C	163.2	175.7	157.8	165.8
Differences				
θ_1, $(\bar{X}_A-\bar{X}_B)$	- 10.0	3.1	- 10.4	1.6
θ_2, $(\bar{X}_A-\bar{X}_C)$	- 16.9	7.4	- 16.5	- 7.7
θ_3, $(\bar{X}_B-\bar{X}_C)$	- 6.9	4.3	- 6.1	- 9.3
σ_e^2	142.7	259.4	83.8	173.0
n	120	120	120	120
q(k, N-k)	4.12	4.12	4.12	4.12

Table 19

Multiple Comparisons

Transport	θ	Confidence interval	Overlap zero
T_2	1	- 5.51 to -14.49	No
	2	-12.41 to -21.39	No
	3	- 2.41 to -11.39	No
T_3	1	9.16 to - 2.96	Yes
	2	13.46 to 1.34	No
	3	10.36 to - 1.76	Yes
T_5	1	- 6.94 to -13.86	No
	2	-13.04 to -19.96	No
	3	- 2.64 to - 9.56	No
T_6	1	6.54 to - 3.34	Yes
	2	- 2.76 to -12.64	No
	3	- 4.36 to -13.24	No

The confidence intervals of θ_1 of T_3, θ_3 of T_3 and θ_1 of T_6 overlap zero. This indicates that the differences between the means of Setups A and B of T_3, Setups B and C of T_3, and Setups A and B of T_6 are not great enough to be attributed to anything but chance alone. Table 20 contains the rank order of the mean values for all twelve operators which could be assigned as the result of the multiple comparisons. It was necessary to split the rank column of T_3 since there were two possible rankings. The multiple comparisons of means showed that Setup A was essentially equal to Setup B, Setup A was greater than Setup C, and Setup B was essentially equal to Setup C. Therefore, as indicated by the tentative rankings under T_3, Setup C could be ranked first and Setup A third. Setup B, not being significantly different from either Setup A or C, must be placed either with Setup A or with Setup C. In the case of T_6, Setup A was proved to be essentially equal to Setup B, but both were less than Setup C. Hence Setups A and B must be ranked together.

Table 20

Rank Order of Mean Values For All Twelve Operators

	T_2		T_3			T_5		T_6	
Setup	$\bar{X}$	Rank	$\bar{X}$	Rank		$\bar{X}$	Rank	$\bar{X}$	Rank
A	146.3	1	183.1	2.5	3	141.3	1	158.1	1.5
B	156.3	2	180.0	2.5	1.5	151.7	2	156.5	1.5
C	163.2	3	175.7	1	1.5	157.8	3	165.8	3

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